Experimental Investigation of the Fundamental Entropy Noise Mechanism in Aero-Engines

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Entropy noise caused by combustors increases rapidly with rising Mach number in the nozzle downstream of the combustion chamber. This is experimentally shown with a dedicated test facility, in which entropy waves are generated in a controlled way by unsteady electrical heating of fine platinum wires immersed in the flow. Downstream of the heating module called Entropy Wave Generator (EWG) the pipe flow is accelerated through a convergent-divergent nozzle with a maximum Mach number of 1.2 downstream of the nozzle throat. Parameters like mass flux of the flow, nozzle Mach number, amount of heating energy, excitation mode (periodic, pulsed or continuously), and propagation length between Entropy Wave Generator and nozzle have been varied for the analysis of the generated entropy noise. The results are compared with the results of a one-dimensional theory found in early literature.

I. Introduction

The total noise emitted by a combustion chamber consists of direct and indirect combustion noise.[1] Only the direct combustion noise is related to the combustion process. Indirect combustion noise also called entropy noise is related to the acceleration of gas temperature nonuniformities caused by the unsteady combustion processes (see also[2–4]). Since the nozzle guide vane (NGV) of the first turbine stage is choked under almost every relevant operation condition of aero-engines, hot spots passing through the nozzle are connected with mass flow variations (monopole sound source) and also with momentum flux variations (dipole sound source). Gas temperature nonuniformities may also be the cause for broadband noise of all turbine stages, since the related density fluctuations cause pressure fluctuations on the blade and vane surfaces of each turbine stage.

Entropy noise receives increased interest by the aero-engine industry because it may have a major contribution to the total noise emission of combustion systems. With the noise reducing improvements achieved on other aero-engine components like e.g. low noise fan design and jet noise reduction by high bypass ratios, the noise concern in aero-engine developments also includes the combustion noise issue. Especially at helicopter engines, which do almost emit no jet noise, the entropy noise seems to be of high importance.

In a review work concerning the different combustion noise sources Strahle[5] concluded that the impact and importance of entropy noise is still controversial in the literature which is mainly caused by the lack of comprehensive experimental investigations in this area. This deficiency of experimental entropy noise research holds even up to now. One of the main challenge in experimentally investigating entropy noise is the separation of direct and indirect combustion noise. Muthukrishnan and Strahle[6,7] separated direct noise sources and entropy noise in a combustor rig via coherence analysis. An experimental approach with generating entropy waves by electrical heaters similar to the test rig presented here was done by Bohn[8] and Zukoski[9] in the seventies. However, the used experimental setup generated only a very low temperature modulation (≈ 1 K) with little parameter variations and the data acquisition and processing system did not allow a high-resolution quantitative signal analysis in the time domain.

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Therefore, the generation mechanisms and parameter dependencies of entropy noise are still not completely explained so far. Hence, this work within the framework of a DFG research unit on combustion noise (`http://www.combustion-noise.de`) presents an investigation of entropy noise phenomena on a reference test rig called Entropy Wave Generator (EWG).

II. Experimental Setup

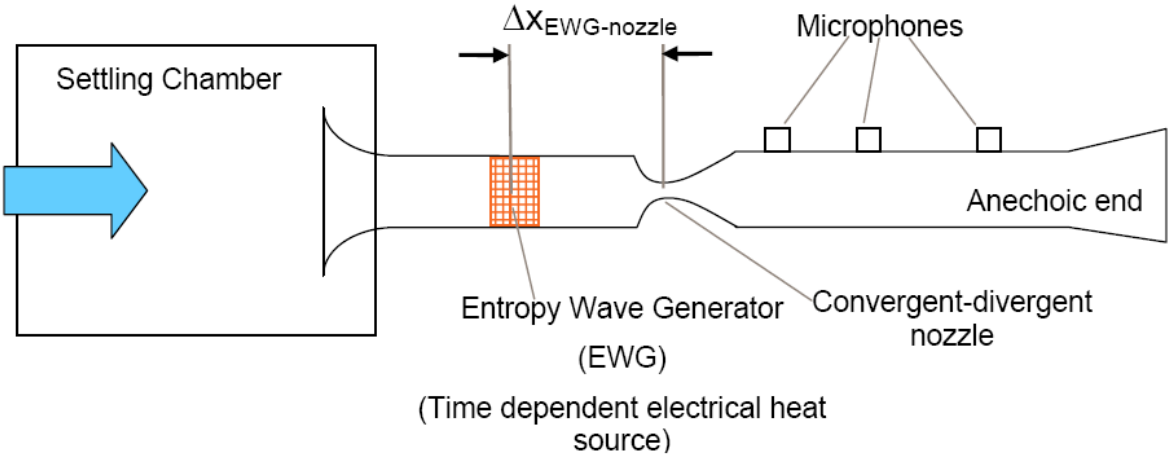

Figure 1. Sketch of the Entropy Wave Generator (EWG).

The Entropy Wave Generator (EWG) is basically an accelerated tube flow with the capability of inducing entropy waves via a heating module. The idea of this setup is to optimize and test detection methods for entropy noise and to study the parameter dependencies of the entropy noise generation mechanism. Furthermore, it allows to validate numerical (CFD + CAA) studies and to confirm theoretical considerations.

A sketch of the design is shown in Fig. 1. The flow, which is supplied by a compressed air system, is calmed in a settling chamber with a honeycomb flow straightener before it enters the tube section via a bell-mouth intake. The inner diameter of the tube is 30 mm. The heating module consists of six ring sections with ten platinum wires stretched across each section. The wires have a diameter of 25 μm and a total length of about 1.2 m. In the current setup the wires can be heated with an electrical power up to 200 W. The length of the heating module in the streamwise direction amounts to 48 mm. The tube section following the heating module is exchangeable so that three different lengths, 42.5, 92.5 and 192.5 mm like shown in Fig. 2 can be tested. Further downstream the flow is accelerated through the convergent part of a convergent-divergent nozzle and then decelerated in the subsonic divergent diffuser part of the nozzle. The following, 1020 mm long tube section has a diameter of 40 mm and is equipped with wall flush mounted microphones at different axial positions for acoustic analysis. The flow leaves the test rig through an anechoic termination in order to minimize acoustic reflections into the measurement section. The maximum mass flux is limited by the air supply to 18 g/s and the maximum Mach number in the nozzle throat amounts to Ma = 1 at a

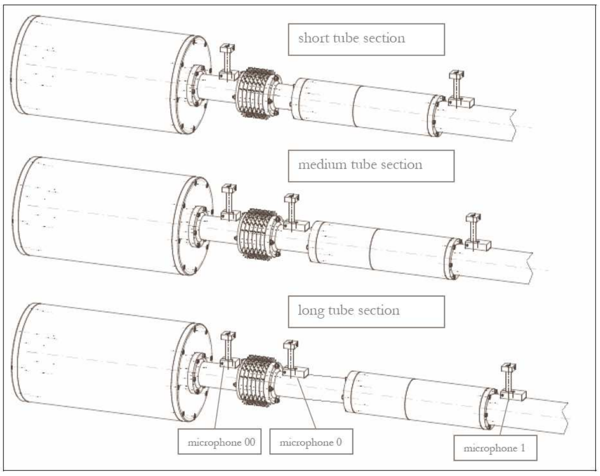

Figure 2. Sketch of the Entropy Wave Generator (EWG) with different tube sections corresponding to different propagation lengths of entropy waves.

mass flux of about 11 g/s and a nozzle diameter of 7.5 mm. In order to obtain information about convecting temperature fluctuations or so called entropy waves, bare wire thermocouples with a diameter of 25 μm are installed between the heating module and the nozzle. A photo of the Entropy Wave Generator is displayed in Fig. 3.

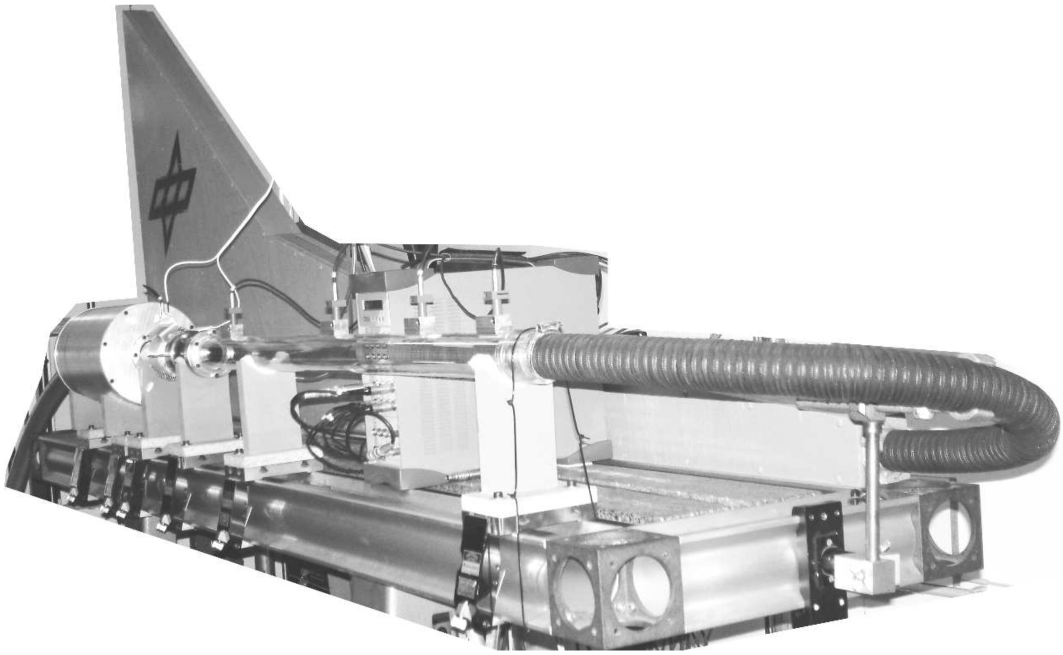

Figure 3. Photo of the Entropy Wave Generator setup.

Since the boundary conditions of this model test rig are well-defined, this set-up is ideally suited for numerical simulations. Therefore, two other research groups of the Combustion Noise Initiative funded by the German Research Foundation (DFG) are conducting numerical studies (CFD / CAA) on the generation and propagation of entropy noise using the model test rig set up and analogue parameter variations.[10]

III. Theoretical Aspects

One of the first analytical considerations of sound generation by accelerated or decelerated entropy waves was published 1973 by Morfey.[3] This work was an extension of the Lighthill theory[11] for jet noise with the so called “excess jet noise” produced by density inhomogeneities in jets like for example in aero-engines. Following this analytical estimation by Morfey, the “excess jet noise” is scaling with the sixth power of the jet velocity. This extension of the Lighthill theory was further developed by Howe[12] describing the noise generation mechanisms in inhomogeneous and non-isentropic flows using an acoustic wave operator.

In 1975 Ffowcs Williams & Howe[13] formulated an analytical expression for the sound generation and propagation of entropy inhomogeneities called slugs or pellets convecting through a nozzle. Using the Green function this formulation of Ffowcs Williams & Howe described the in-duct as well as the free field radiation of entropy induced sound in the time domain but it was restricted to low Mach number flows.

The generation mechanism of entropy noise in one dimensional nozzle flows is characterized by Marble & Candel[4] for compact nozzles with subsonic and supersonic flow and supersonic flow with normal shocks. Here the compactness of the nozzle stands for a very small length of the nozzle in comparison to the wavelengths of the corresponding entropy and sound pressure waves. Marble & Candel derived expressions for the up- and downstream propagating acoustic pressure perturbations generated by both impinging entropy disturbances and impinging acoustic pressure waves. Therefore, these expressions result in the following three quasi transfer functions for either nozzle or diffuser configurations with subcritical mean flow conditions (see also [14]):

- For a sound pressure wave caused by entropy fluctuations:

$$p'_{2+} = \frac{M_2 - M_1}{1 + M_2} \frac{\frac{1}{2} M_1}{1 + \frac{1}{2}(\kappa - 1) M_1 M_2} a_1^2 \text{ A } \varrho'_s \tag{1}$$

- For the transmission of an entropy wave:

$$\varrho'_{s2} = \left(\frac{1 + \frac{\kappa - 1}{\kappa} M_1^2}{1 + \frac{\kappa - 1}{\kappa} M_2^2} \right)^{\frac{1}{\kappa - 1}} \varrho'_s \tag{2}$$

- For the transmission of an acoustic pressure wave:

$$T := \frac{p'_{2+}}{p'_{1+}} = \frac{1 + M_1}{M_1 + M_2} \frac{2M_2}{1 + M_2} \frac{1 + \frac{1}{2}(\kappa - 1) M_2^2}{1 + \frac{1}{2}(\kappa - 1) M_1 M_2} \text{ A} \tag{3}$$

- with

$$\text{A} = \left(\frac{1 + \frac{1}{2}(\kappa - 1) M_1^2}{1 + \frac{1}{2}(\kappa - 1) M_2^2} \right)^{\frac{\kappa}{\kappa - 1}} \tag{4}$$

where κ is the isentropic exponent, M_1 and M_2 the Mach numbers upstream and downstream of the nozzle or diffuser, respectively, p'_{1+} the impinging acoustic pressure wave, ϱ'_s the impinging density fluctuation corresponding to the entropy wave, ϱ'_{2s} the transmitted density fluctuation through the nozzle or diffuser, a_1 the speed of sound upstream of the nozzle or diffuser and p'_{2+} the downstream propagating acoustic pressure wave.

The results of this one dimensional approach are compared with experimental data of this work in the result section.

IV. Measurements and Results

The first series of measurements aim to identify and separate the entropy noise from noise related to other sources. One of the most characteristic features of entropy noise is the slow propagation velocity of entropy waves or hot spots with the flow velocity compared to acoustic waves which propagate with the speed of sound. In the test rig the flow velocity of the tube flow is about two orders of magnitude lower than the speed of sound.

The second part of measurements is a parametric study in order to evaluate the dependencies of entropy noise on the nozzle Mach number and the amplitude of the temperature or entropy perturbation.

Finally these results are compared with the theoretically predicted values from the one-dimensional theory of Marble & Candel.[4]

A. Entropy Noise Identification:

In order to identify the generated entropy noise the Entropy Wave Generator (EWG) response was investigated using two different excitation modes:

1. In a pulse excitation mode Microphone signals were analyzed in the time domain in a pulse excitation mode. The platinum wires of the EWG rig were heated once per second, controlled by square-pulses from a function generator.

2. The cross-spectral analysis of microphone signals and excitation signals of the EWG module as a reference was evaluated while the EWG was heated periodically.

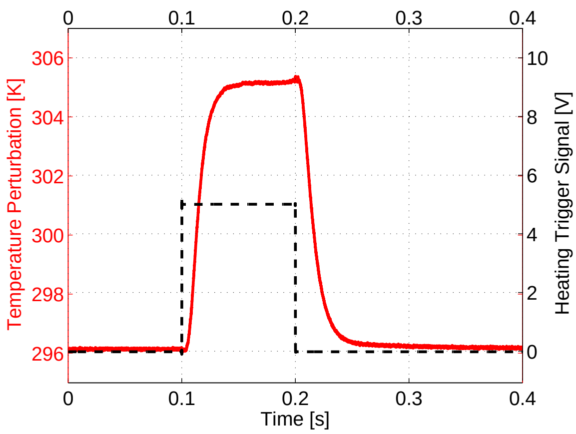

Figure 4. Convecting entropy wave (solid red line) in terms of flow temperature perturbation measured by a fast thermocouple downstream of the heating module; the dotted black line shows the heating trigger signal.

In the time domain analysis of the pulse excitation mode, a distinct propagation delay between the excitation signal and the generated acoustic pressure pulse downstream of the nozzle can be detected. This time delay results mainly from the distance between heating module and nozzle divided by the tube flow velocity upstream of the nozzle.

Figure 4 displays the convecting entropy or temperature perturbation (solid red line) measured by a fast thermocouple located 34 mm downstream of the heating module. The dotted black line indicates the heating trigger signal. The run of the red curve reveals a temperature rise from the steady flow temperature of 296 K up to 305 K following the heating trigger with a certain propagation delay between the heater module and the temperature position. However, the exact edge shape of the entropy wave is not clearly determined since the temperature signal is certainly affected by the limited frequency response of the thermocouple (see also[15]).

In the first part of the parametric study this distance as well as the flow velocity has been varied in order to generate different propagation delays of the entropy waves. For each parameter variation an ensemble average over 300 single pulse traces was evaluated.

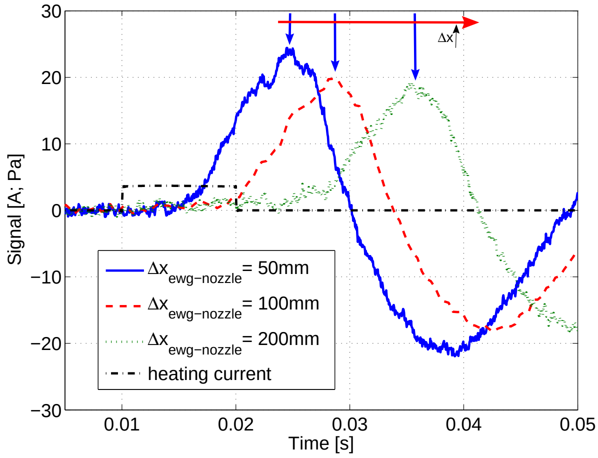

Figure 5. Phase averaged time series of EWG microphone signals in the pulse excitation mode for different tube lengths Δx between heating module (EWG) and nozzle.

Figure 5 shows the acoustic pressure pulse signals of three different measurements with different tube lengths between the heating module and the nozzle. Here, the bulk velocity in the tube section was 11.9 m/s and the Mach number in the nozzle Ma $= 1$. The heating current signal is also plotted in the graph as a dashed line. A positive temperature perturbation induced by the heating of the platinum-wire module generates accelerated through the nozzle a positive pressure pulse. This pressure pulse propagates in the tube section downstream of the nozzle and is detected by the wall-flush mounted microphones. The propagation delay of the entropy noise pressure pulse is equivalent to the propagation path length between EWG and nozzle throat. With increasing tube length the time delay of the pressure pulse increasing, too. The amplitudes of the pressure pulses decrease slightly with increasing duct length probably due to an increased dispersion of the entropy waves.

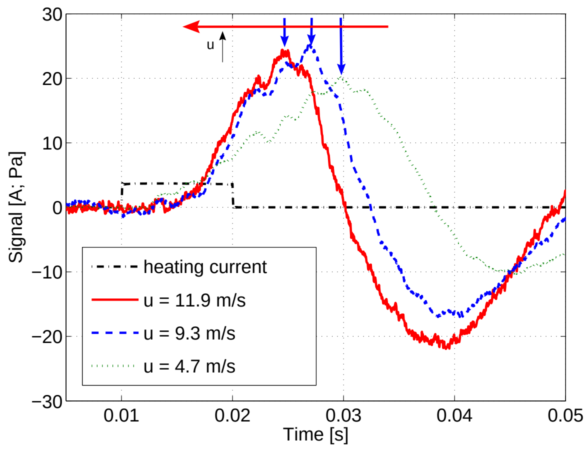

Figure 6. Phase averaged time series of EWG microphone signals in the pulse excitation mode at different bulk velocities.

The flow velocity and therewith the convection velocity of the entropy waves is varied in Fig. 6. It can be seen that the increase of the bulk velocity yields a corresponding decreased time delay and an increased pressure amplitude. The maximum Mach number at this measurement series was Ma $= 1$.

The propagation or convection time of the entropy waves can also be determined by cross-spectral analysis of microphone signals and excitation signals in the periodical (sinusoidal) forced mode. In this case the slope of the linear phase relation in the cross spectrum is anti-proportional to the propagation speed of the entropy wave. This analysis is applied to the next part of the experimental study.

Figure 7 shows the phase plot of the cross spectra between heating current and microphone signals downstream of the nozzle for an excitation sweep from about 85 to 145 Hz. The different traces correspond to different tube lengths between EWG and nozzle throat. The longest distance ($\Delta x_{\text{ewg-nozzle}} = 205$ mm) results in the steepest phase line due to the same propagation velocity.

From this phase relation the propagation velocity can be quantified like shown in Tab. 1. Here, the second column displays the time delays resulting from the slope of the phase relation at different tube lengths (column one). Considering the acoustic propagation time of the generated entropy noise the traveling speed of the entropy waves can be determined (column three). These phase velocities show a good agreement compared to the bulk velocity of the flow (column four). However, it has to be considered that the tube flow features a certain flow profile, where the bulk velocity, calculated from the mass flux, the tube cross-section and the mean density, is only a spatial mean value.

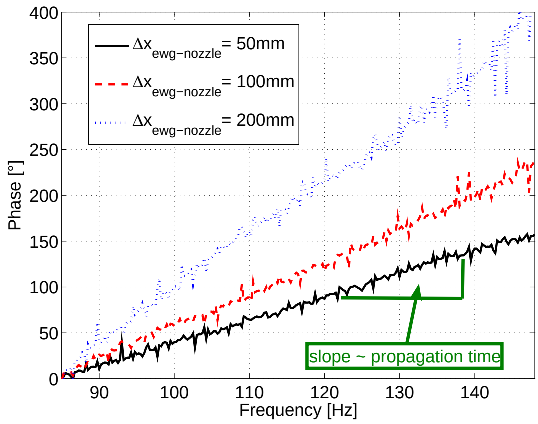

Figure 7. Phase relation of cross spectra between heating current and microphone signals downstream of the nozzle for different tube length Δx between heating module (EWG) and nozzle.

Table 1. Propagation velocities of entropy waves calculated from phase relation in comparison with the bulk velocity of the flow for different tube length Δx between heating module (EWG) and nozzle.

Distance $\Delta x_{\text{ewg-nozzle}}$ [mm]	Time Delay [ms]	Propagation Velocity [m/s]	Bulk Velocity [m/s]
55	6.9	11.7	11.9
105	9.9	13.6	11.9
205	18.1	12.8	11.8

B. Study on Parameters of Entropy Noise:

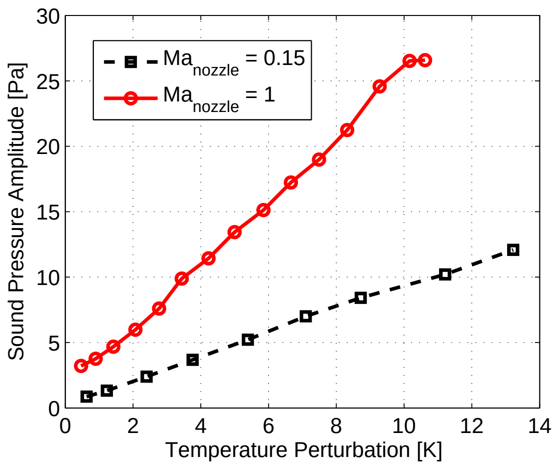

Figure 8. Acoustic pressure pulse amplitude of generated entropy noise over accelerated temperature perturbation amplitude for two different nozzle Mach numbers $\text{Ma}_{\text{nozzle}} = 0.15$ and $\text{Ma}_{\text{nozzle}} = 1$.

In order to evaluate the different parameters of entropy noise generation a test series was conducted varying the mass flux and therewith the nozzle Mach number as well as the amplitude of the temperature perturbation. The amplitude of the generated entropy noise was determined by extracting the acoustic pressure pulse amplitude of a microphone downstream of the nozzle. The nozzle Mach number was changed from 0.15 up to 1.0 with amplitudes of temperature fluctuations between 1 and 13 K measured by using a bare thermocouple with a diameter of 25 μm installed downstream of the heating module.

An insight into the functional characteristics of Mach number and temperature as parameters for entropy noise is provided by Figures 8 and 9. Figure 8 shows an almost linear relation between the temperature perturbation amplitude and the generated entropy noise amplitude for two different Mach numbers $\text{Ma}_{\text{nozzle}} = 0.15$ and $\text{Ma}_{\text{nozzle}} = 1$.

In contrast to the temperature, the dependency of entropy noise on the Mach number is not linear as to be seen in Fig. 9 for two different temperature perturbation amplitudes 7.5 K and 9 K. For low nozzle Mach numbers up to 0.7 the entropy sound pressure amplitudes are increasing with the Mach number. Above a nozzle Mach number of ≈ 0.7 the entropy sound pressure amplitude is decreasing again. An explanation of this behavior could be the low acoustic transmission coefficient of the divergent part of the nozzle. This behavior is also prescribed by Marble & Candel[4] with the acoustical characteristics of a diffuser flow at high inlet Mach numbers.

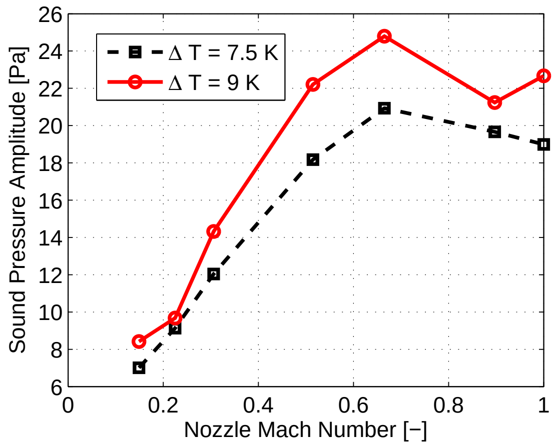

Figure 9. Acoustic pressure pulse amplitude of generated entropy noise over nozzle Mach number for two different amplitudes of accelerated temperature perturbation.

Comparison with Theoretical Prediction:

The one dimensional theory of Marble & Candel[4] describes in principle only the generation of entropy noise for either a nozzle or a diffuser separately. Since in the experimental setup a convergent-divergent nozzle was investigated, a combination of the theoretical expressions concerning the nozzle and the diffuser part of the setup is necessary. For the comparison with the experiment, the downstream propagating entropy pressure amplitude generated in the nozzle has to be multiplied by the transmission factor of the subsequent diffuser flow. Furthermore, the pressure wave generated by the deceleration of the entropy wave in the diffuser has to be summed up to the total downstream propagating sound pressure wave, which in the experiment is measured by the microphones in the duct section downstream of the nozzle.

Figure 10 shows the comparison of the experimental microphone data with the theory of Marble & Candel.[4] It displays the entropy sound pressure amplitude normalized by the total pressure and the relative temperature perturbation over the nozzle Mach number. For each Mach number different temperature amplitudes have been investigated in the experiment (see Fig. 8) resulting in black several marker points for a certain Mach number in Fig. 10.

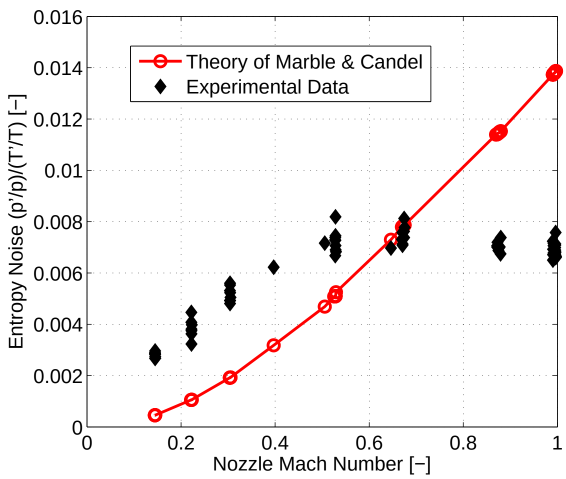

Figure 10. Comparison of experimental data with theoretical prediction; normalized entropy sound pressure over nozzle Mach number.

For low Mach numbers the theoretical results are lower then the acquired data whereas for higher nozzle Mach numbers between 0.5 and 0.7 the predicted values show a good agreement with the experimental data. For a choked nozzle ($\mathrm{Ma}_{\mathrm{nozzle}} = 1$) the measured entropy noise amplitudes are lower than the theoretical ones. The differences are not fully understood until now. Possible explanations are the compactness assumption in the theory (nozzle short in comparison with the wave length) and the one-dimensional concept of the theory. The theory implies the nozzle length to be much smaller than the wavelength of the entropy and sound waves. Especially for the entropy wave, which has due to the low propagation speed a very short wavelength, this assumption may not be valid anymore. Furthermore, any radial velocity and acceleration components, which are present in the experimental nozzle flow, are not included in the one-dimensional theory.

V. Conclusion

Entropy noise was investigated in a dedicated test facility, in which entropy waves are electrically generated and accelerated through a convergent-divergent nozzle. A parameter study on the entropy noise generation mechanism showed the expected linear dependence of the induced entropy sound pressure amplitude and the amplitude of the entropy or temperature perturbation. The correlation of the entropy noise with the nozzle Mach number indicated a strongly increasing entropy noise pressure with the Mach number for low Mach numbers, whereas for Mach numbers higher than 0.8 the entropy noise is slightly decreasing. The comparison of the measured entropy noise with the theory of Marble & Candel[4] showed a quite good agreement in consideration of the one-dimensional description of the theory. In this work the influence of the exact shape of the entropy waves with respect to the generated entropy noise level was not explicitly investigated. For future investigations a modification of the heating control is currently under development in order to generate different edge shapes of the entropy waves.

Acknowledgment

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